Monitoring Human Performance during Suited Operations: A Technology Feasibility Study Using EMU Gloves

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Mobility tracking of human subjects while conducting suited operations still remains focused on the external movement of the suit and little is known about the human movement within it. For this study, accelerometers and bend sensitive resistors were integrated into a custom carrier glove to quantify range of motion and dexterity from within the pressurized glove environment as a first stage feasibility study of sensor hardware, integration, and reporting capabilities. Sensors were also placed on the exterior of the pressurized glove to determine if it was possible to compare a glove joint angle to the anatomical joint angle of the subject during tasks. Quantifying human movement within the suit was feasible, with accelerometers clearly detecting movements in the wrist and reporting expected joint angles at maximum flexion or extension postures with repeatability of ±5º between trials. Bend sensors placed on the proximal interphalangeal and distal interphalangeal joints performed less well. It was not possible to accurately determine the actual joint angle using these bend sensors, but these sensors could be used to determine when the joint was flexed to its maximum and provide a general range of mobility needed to complete a task. Further work includes additional testing with accelerometers and the possible inclusion of hardware such as magnetometers or gyroscopes to more precisely locate the joint in 3D space. We hope to eventually expand beyond the hand and glove and develop a more comprehensive suit sensor suite to characterize motion across more joints (knee, elbow, shoulder, etc.) and fully monitor the human body operating within the suit environment.

Nomenclature

EVA	=	Extravehicular Activity
JSC	=	Johnson Space Center
BSR	=	Bend Sensitive Resistor
MCP	=	Metacarpophalengeal
DIP	=	Distal interphalangeal
PIP	=	Proximal interphalangeal
TMG	=	Thermal micrometeroid garment

I. Introduction

THE pressure bladder and outer material of EVA gloves restrict movement, resulting in a loss of mobility and overall dexterity during EVA tasks. When pressurized to 4.3psid, the Phase VI EVA gloves have shown to

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provide approximately 20% of barehanded range of motion, and approximately 20% of barehanded grasping strength[1]. Thus the increased force required to successfully perform actions while gloved has a direct impact on human performance and ability to complete a task in a timely and efficient manner.

This investigation was a task under the High Performance EVA Glove (HPEG), an element of the Next Generation Life Support (NGLS) funded by the Space Technology Mission Directorate (STMD). With additional support from the EVA Physiology Laboratory at JSC, the task aims to determine if range of motion can be determined using flex sensors and accelerometers to monitor the difference in joint angle between glove models. In addition to determining if it is feasible to compare a glove joint angle to the anatomical joint angle of the subject at the same time during a task to better understand how the human body moves inside the suit hardware. A carrier glove with integrated sensors (hereafter referred to as the *sensor glove*) was developed for this test. This sensor glove was worn by the test subjects while they performed a series of common gloved tasks and hand postures.

This initial study looked at the efficacy of using these sensors to determine how range of motion and dexterity are impacted by the pressurized glove and quantify this impact in an effort to influence future design decisions to improve the comfort and mobility of gloves.

II. Sensor glove fabrication and test procedure

A. Sensor glove fabrication and sensor placement

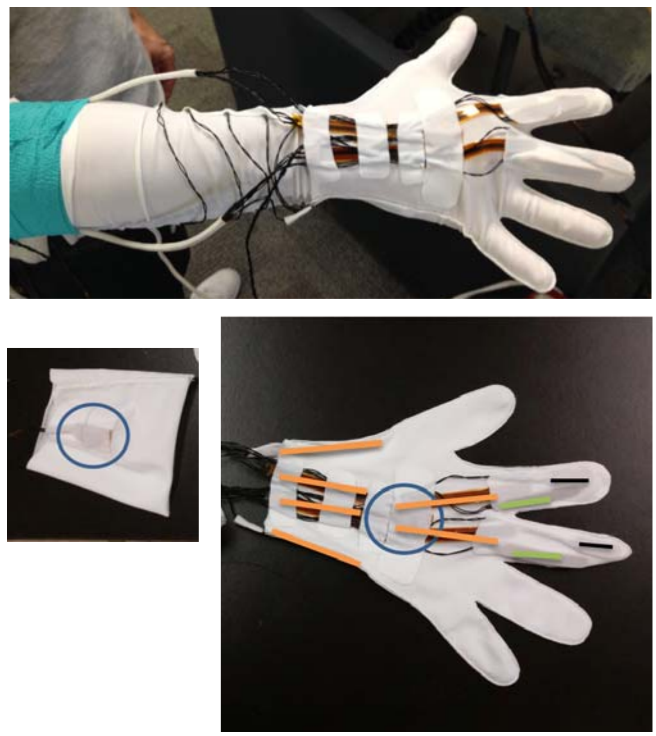

Figure 1. Sensor glove, and forearm band. All wiring leading to data acquisition hardware was adhered to the subjects arm using athletic tape (teal band). Circled in blue are the two accelerometers, Orange represents locations for 3” bend sensors, green 2”, and black 1”. The sensors needed to be slightly offset from the finger joint center to accommodate the wiring being passed from the more distal sensor.

The primary purpose of this study was to evaluate sensor technologies and implementation methods within a space suit environment. The sensor glove, shown in Figure 1, which houses 10 bend sensitive resistors (BSRs) (Tactilus Flex Sensor with polyimide coating, Flexpoint Sensor Systems Inc. Draper, UT) and a tri-axial accelerometer (MEMSIC MXR9500G/M, MEMSIC Inc. Andover, MA) was worn inside the space suit glove in place of the standard comfort glove. The bend sensors used vary in length from 1 to 3 inches, and are made with a printed conductive ink that acts as a variable resistor when bent, where increases in angle of bend from a flat state result in an increase in resistance. The accelerometer provides an output voltage relative to the current position in 3D space, allowing us to place the hand at a particular angle relative to its initial position and any other accelerometers present one each axis. An additional accelerometer was placed just below the elbow on the subject’s upper forearm using a fabric band.

BSRs were placed on the index and middle finger distal interphalangeal (DIP), proximal interphalangeal (PIP) and metacarpophalangeal (MCP) joints ranging in lengths of 1” to 3” respectively. Additionally four 3” sensors were placed on the wrist to capture flexion, extension, adduction, and abduction of the joint. The assumption for this placement was that the shorter sensors might be better suited for the smaller joints, while larger movements would warrant a longer sensor. The sensors used are unidirectional and will only report accurately when bent into a flexion position. In order to capture the extension posture of the wrist, one of the two is placed in a reverse direction.

On the exterior, exposed to the glove box environment, 3” bend sensors were adhered to the MCP and PIP joints of the index and middle fingers of the glove. Additionally two accelerometers were placed at similar locations to that of the inside of the glove. This was intended to determine both our ability to place sensors inside a glove box during

testing and offer the ability to compare internal and exterior joint angles between the wearer and the glove hardware itself.

B. Test procedure

All tasks were tested in a glove box environment de-pressurzied to 10.4psia to mimic the 4.3psig of the suit in normal operation. Both subjects in this study are right hand dominant. Subjects were tasked with mimicking a series of hand postures, grasping cylinders of increasing diameter, and performing a dexterity intensive task. Each test scenario was completed with the Phase VI and Series 4000 gloves, in addition to a baseline test of just the sensor system (dubbed *ungloved*). All tasks were completed for each glove in series before changing glove models. Sensors placed on the exterior of the TMG layer were removed and replaced to a new glove as needed with care to place them as similarly as possible to their prevous position where possible. These tasks were selected based on previous glove studies conducted by various groups at JSC and represent much of the range of motion and hand dynamics needed while conducting an EVA.

Having donned the sensor glove, subjects were first tasked with placing their hands in a series of postures and holding that position for 5 seconds. Seven postures were tested, and repeated 3 times each for each glove case (ungloved, Series 4000, Phase VI).

The neutral wrist position of all the postures is presented in Figure 2a. In addition to the neutral wrist position, maximal wrist flexion and extension was also tested for these postures.

Following completion of all hand postures subjects were asked to grasp a a hollow polycarbonate tube and maintain a light grip for 5 seconds. Tubes ranging in diameter from ¾" – 2 ¾" at ½" intervals were used for this task. An example is shown in Figure 2b.

The ultimate goal for this work is to have the capability to monitor dynamic human movements in the space suit environment over what may be unknown tasks at unknown joint positions. The final task in the test series aims to address this and determine if the sensor glove can be used to quantify and track a dynamic movement. Subjects were asked to complete a dexterity task consisting of grasping a U-bolt from the board, rotating it 90 degrees, and replacing it into the board (Figure 2c). This task was timed for each test configuration but the subject's performance wearing the sensor glove inside the suit glove is secondary to the goal of determining if the overall task can be quantified by the sensors.

In one test, conducted at a later date with different subjects, the Phase VII-D glove was also added to the test profile. This test was done with solely accelerometers, and subjects were only tasked with wrist flexion and extension postures, and the dexterity task.

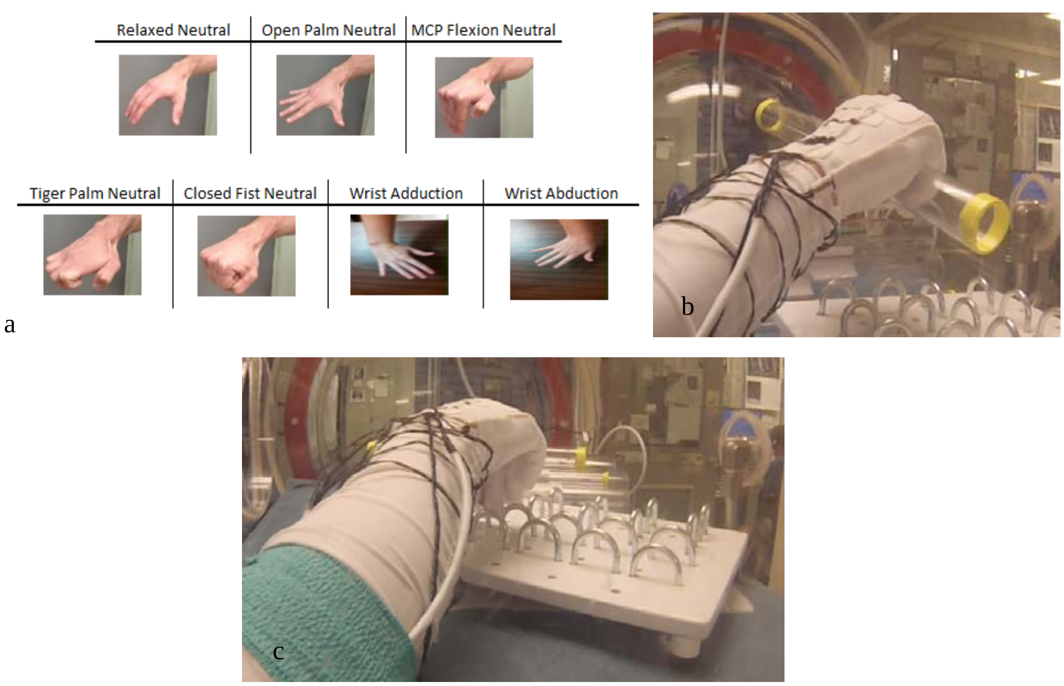

Figure 2. a), Neutral hand postures. All postures except Wrist Adduction and Wrist Abduction were also done at max wrist flexion and extension positions for each test case. b), Tube grasping task. c), Peg relocation task. All images shown are taken during the ungloved test case.

III. Results and Discussion

The angle orientation for the data is shown in Figure 3 for flexion and extension positions. Angles are reported in reference to a 180 degree bend representing a neutral/flat sensor position. Bend sensors were calibrated by placing the sensors in known angles and measuring the resistance to create a calibration curve following a procedure by Gentner et al.[2]. The resistance-angle relationship carries with it an assumption that changes in resistance are caused by flexion movements since the sensors are uni-directional. There will be instances where the sensor may bend outside its design specification yet still report a resistance value that correlates with an angle on the calibration curve.

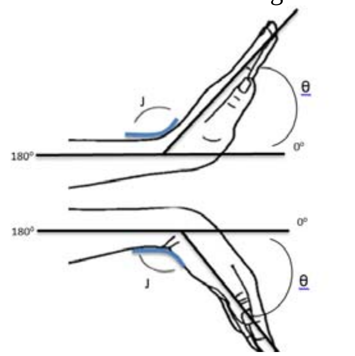

Figure 3. Method of joint angle reporting. Angles are measured by the deflection angle of the sensor during test (θ), and corrected for the actual joint angle (J) during post processing.

Accelerometers were used to quantify wrist flexion and extension movements only, along a single axis. Calibration of these sensors mainly consisted of verification of correct voltage output by placing them flat on a surface, and at ±90^{o} positions. Wrist flexion and extension angles are calculated by subtracting the angle reported by the accelerometer at the back of the hand from that on the back of the forearm. This allows one to differentiate between movement of the wrist joint versus tilting of the whole arm.

A. Bend Sensor Results

1. Hand postures task

Bend sensors act as a variable resistor as a result of changes to the structure of the conductive ink that occurs as they flex. The sensors used here are uni-directional, meaning that bends opposite of their designed direction will result in inconsistent resistance values. For extension postures, this poses a problem since they cannot accurately reflect the negative angle of deflection they undergo. Only the "Wrist Extension" sensor was placed in reverse in an effort to capture this movement. It is assumed for the finger joints that an extension beyond 180^{o} is not possible during the postures task as this only occurs during pinch-grip type tasks.

Observations by researchers during testing showed that the stiffness of the sensor material typically results in a bend about a single point which results in a large overestimation of the actual angle of the bending structure. Therefore, as a means of approximating a current joint position, the bend sensors appear to be an appropriate tool, however precisely measuring the actual joint angle did not prove possible. The tiger palm, and closed fist postures illustrate this shortcoming. At these postures the index and middle finger DIP and PIP joints approach a 90 degree bend. The flex sensors located at those joints on the sensor glove however report a value near 150±5 and 130±8 degrees respectively.

Figure 4. MCP sensor "pillowing" as a result of the elastic fabric and adhesives pulling on the sensors

The MCP joint was instrumented with a 3" sensor that repeatedly bent incorrectly as a result of the sensor glove fabric "pillowing" up under it (Figure 4). In many cases angles approaching 90^{o} at postures where the MCP was actually flat were reported. This was most noticeable in the ungloved cases. It is assumed that the bladder of the spacesuit glove helps to dampen this "pillowing" by compressing the sensor glove. Table 1 highlights the overall sensor readings from all finger joints.

Four sensors were also placed on the area surrounding the wrist. Unfortunately the sensors reported almost no change in angle regardless of posture for most of the trials and did not indicate any particular posture for either flexion or extension poses, even during the wrist specific postures. Poor sensor placement is believed to be responsible for this. Review of the test video showed that the sensors on the glove slide up the back of the hand during full flexion and remain relatively flat (Figure 5). The wrist extension sensor does indicate that it has been bent, however the change only appeared to be on the order of ±5^{o} at a full extension versus a neutral pose which due to the inherent variability in the sensor is not enough to gauge movement. This was the case for all wrist postures including adduction and abduction.

Posture	1"	2"	3"
Relaxed Neutral	164.6±0.47	147.74±0.49	136.72±6.33
Relaxed Max Flexion	164.79±0.43	147.83±0.47	135.05±7.1
Relaxed Max Extension	164.69±0.46	147.87±0.48	123.96±12.73
Open Palm Neutral	164.99±0.55	148.06±0.53	134.21±7.02
Open Palm Max Flexion	165.02±0.53	148.2±0.55	134.62±8.68
Open Palm Max Extension	164.97±0.44	147.2±2.05	110.38±19.02
MCP Flexion	164.59±0.53	145.41±2.63	118.73±12.32
MCP Flexion Max Flexion	164.64±0.46	146.55±1.59	122.65±10.43
MCP Flexion Max Extension	163.16±2.72	144.52±4.7	124.58±7.15
Tiger Palm Neutral	155.87±3.5	131.69±7.02	135.08±5.95
Tiger Palm Max Flexion	157.86±2.69	134.27±6.32	134.6±4.45
Tiger Palm Max Extension	157.75±3.48	133.21±5.7	120.85±15.64
Closed Fist Neutral	160.33±1.63	131.18±6.16	125.77±3.26
Closed Fist Max Flexion	160.62±1.75	133.56±5.94	125.81±3.76
Closed Fist Max Extension	161.07±2.3	136.78±7.86	127.01±7.6
Wrist Adduction	164.47±0.65	146.86±0.52	129.76±7.68
Wrist Abduction	164.77±0.61	147.28±0.49	130.89±9.19

Table 1. Average sensor angles reported for each posture from inside the glove for all finger joints based on sensor length. Joints are instrumented accordingly: 1"= DIP; 2"= PIP; 3"= MCP. Wrist postures are included in this summary, however wrist sensor values are not a component of the 3" sensor average.

Figure 5. Sensors placed on the wrist (black) appear to move up towards the palm at max flexion which results in a reduced bend than actual wrist movement.

Sensors were also placed on the exterior of the TMG layer at the Index and Middle PIP and MCP joints. The angles reported for these joints varied little between subjects and between postures on average. This may be due to the stiffness of the outer layer not resulting in much change to the sensor angle, or poor placement relative to the interior finger joints. In cases where it is expected to see high joint angles reported (ex: closed fist, tiger palm, MCP flexion) the sensor output matched that of a relaxed pose.

2. *Tube grasping task*

While the hand postures task provided an overall baseline of the minimum and maximum extremes of the subjects' joint angles, the tube grasping task was intended to show how the angle changed through a movement. As the diameter size of the tube increases it is expected to see an increase in the angle of the sensor. This was the case for most of the index and middle finger joints, with the 2" sensor located at the PIP joint reporting as expected during this task(Figure 6).

At the TMG side similar results to the hand postures task was observed for the both PIP and DIP joints on the Index finger with little to no change in bend sensor angle reported. At the middle finger, the DIP joint also remained unchanged, however the PIP joint registered a slight change in angle over the course of diameter differences. This was only the case for the Phase VI test (Figure 7**Error! Reference source not found.**) and highlights the importance of accurate placement across the joint of the sensors. It should be reiterated that between tests of subjects the sensors were moved from the Series 4000 glove to the Phase VI glove and vice versa. This movement may have resulted in better placement on the joint angle as the test proceeded and test personnel better understood the dynamics of the sensor movement during the tasks resulting in this better reporting compared to the hand postures task.

3. *Dexterity task*

The dexterity task consisted of removing, rotating, and replacing 10 U-bolts into a peg board. This was meant to determine if a dynamic task can be tracked and identified using the sensor glove. If a series of voltages or angles are reported it may possible to approximate what action was just undertaken by the subject, based on an existing baseline characterization of several tasks. Data collected using the BSRs for this task was quite variable. It was possible however to glean a somewhat cyclical pattern of the Index and Middle fingers opening and closing in unison as each bolt was grasped. While not perfectly able to capture 10 bolt movements they were able to show that joints are performing similar actions repeteivitly to complete the task. This pattern is most noticed on the MCP and PIP joints as shown in Figure 10 in the Appendix. Table 2 compares the average high –low angle range of the movement by the finger joints for each test configuration from inside the glove. A larger difference indicates a greater flexion range of the joint was possible and may be indicative of a more flexible glove model.

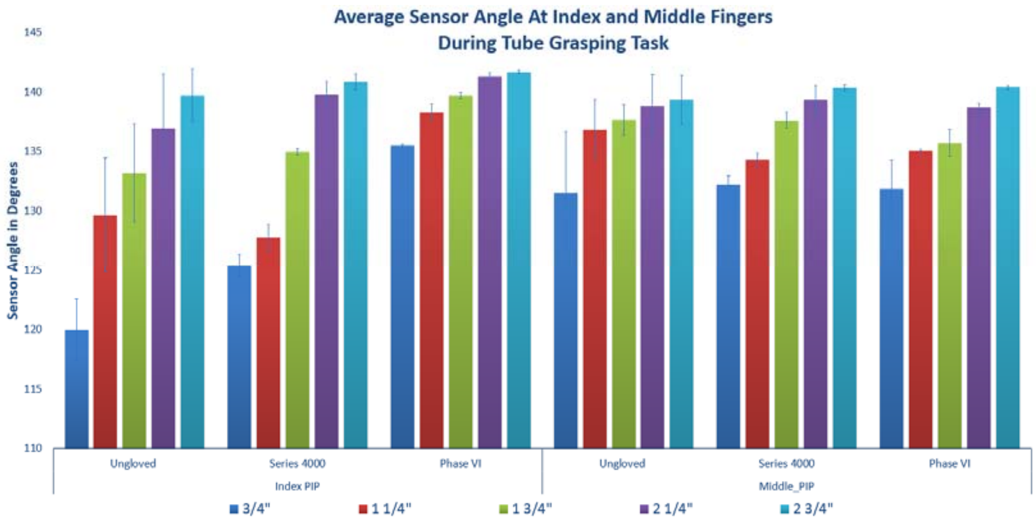

Figure 6. Average sensor angles for index and middle fingers. Data collected using BSRs on the sensor glove from inside the Series 4000 and Phase VI gloves.

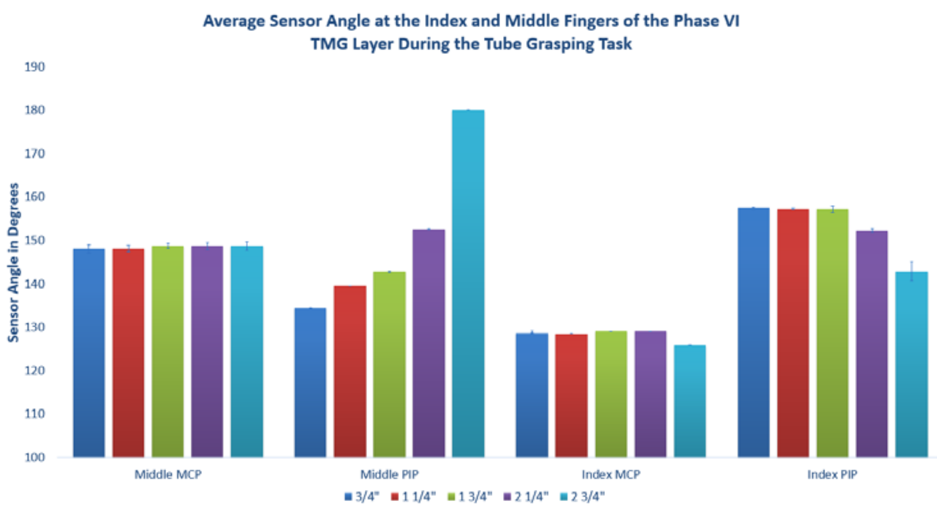

Figure 7. Average sensor angles for the Index and Middle fingers of the Phase VI glove. Data collected using BSRs which are adhered to the outside of the glove.

Test Condition	Index DIP	Index PIP	Index MCP	Middle DIP	Middle PIP	Middle MCP
Ungloved	12.46±4.7	5.87±3.1	5.84±2.2	5.32±0.4	4.06±1.5	1.74±0
Series 4000	5.13±0.3	12.06±1.7	16.59±4.8	5.62±5.4	8.4±0.1	8.85±0.3
Phase VI	4.6±3.6	10.35±6.6	13.57±6.7	4.3±2.2	5.95±7.4	9.12±0.3

Table 2. Average angle range of finger joints taken from inside the glove during the dexterity task. Angles are calculated from the maximum and minimum flexion angles recorded during the task.

B. Accelerometer Results

1. Hand postures task

Accelerometers were placed on the back of the hand and on the upper forearm as shown in Figure 1. The accelerometers provide three ratiometric analog outputs that can measure both dynamic acceleration (e.g. vibration) and static acceleration (e.g. Gravity). In this study only one axis is used to track movement at the wrist for a static acceleration. Two reference points were needed in order to differentiate between tilts of the whole arm and bends at the wrist. Joint angles were calculated by subtracting the reported angle of the roll axis from the hand accelerometer from that of the forearm accelerometer. The angles reported are in reference to 180^{o} representing an unbent state (see Figure 3) and for this data set only postures with flexion and extension of the wrist is reported.

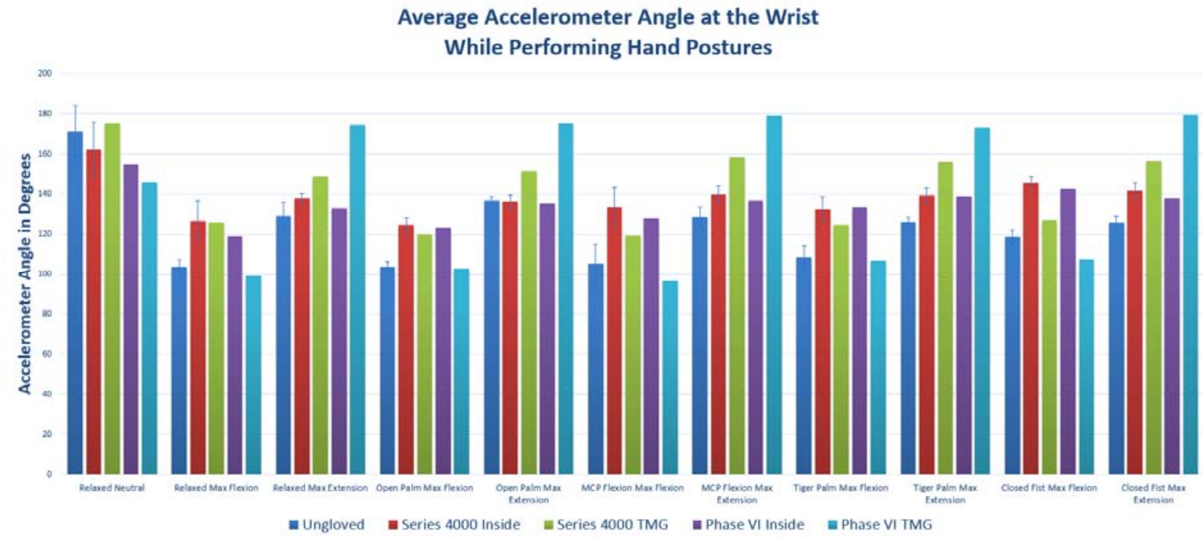

Figure 8. Accelerometer results during the hand postures task. Data is collected for the flexion and extension movements only.

Data collected from both test subjects was very consistent, with clear differences between extension and flexion movements (Figure 8). With the accelerometers it was also possible to compare the exterior glove angle to that of the user with great repeatability across trials and subjects. When comparing the TMG and interior accelerometer data there is clearly a difference between the flexion and extension postures. A larger angle at the TMG side than in the interior of the glove during extension and a smaller angle during flexion is present , indicating that the human joint is bending more from the neutral position than the corresponding glove joint.. This is this case for all flexion and extension movements (Table 3). It was not expected that the TMG layer will be bending more than the wrist joint of the subject. One possible explanation for this in the extension postures is that the folding of the TMG soft goods is affecting the recording, once again highlighting the need to characterize proper placement of sensors in the future prior to a test.

Posture	Series 4000	Phase VI
Relaxed Neutral	13.24	-9
Relaxed Max Flexion	-0.98	-19.71
Relaxed Max Extension	11.12	41.61
Open Palm Max Flexion	-4.28	-20.78
Open Palm Max Extension	15.12	40.02
MCP Flexion Max Flexion	-13.75	-31.5
MCP Flexion Max Extension	18.71	42.25
Tiger Palm Max Flexion	-7.96	-26.26
Tiger Palm Max Extension	16.66	34.07
Closed Fist Max Flexion	-18.5	-34.94
Closed Fist Max Extension	14.95	41.37

Table 3. Angle difference between TMG layer and interior sensors. Negative angle values indicate that the TMG layer achieves a sharper angle than the glove wearer, and vice versa.

2. Tube grasping task

This task was intended to gauge finger mobility moreso than wrist mobility. Therefore it was expected to see that the accelerometers tracking the wrist would remain near 180^{o} for the full suite of tube sizes tested and this was indeed the case as shown in Figure 11 in the Appendix. Regardless of glove it would appear grasping was done in close to a neutral wirst pose by both subjects .

3. *Dexterity task*

There were 10 bolts placed in two rows of five each in each trial. Similar to the bend sensors, while there is no distinctly obvious bolt by bolt record, there is a pattern present of a joint moving through a fairly repetitive bending range.. In one case it was possible to discern when the second row of bolts was started which is shown in Figure 9. The second row of bolts is below the first so a slightly sharper tilt in the wrist was needed to reach these and this is clearly indicated by the data. When comparing the Series 4000 to the Phase VI glove model there is some indication that the Phase VI allows the hand itself more range of motion, as well as the glove itself. The Phase VI glove regularly achieved 120-140 degrees with the wrist itself above 140^o; meanwhile the Series 4000 achieved more in the 140-160 degree range with the wrist occasionally exceeding 140^o but typically maxed out in the 150^o. Table 4 summarizes the average range of wrist flexion and extension motions acheived throughout the task for each glove model tested.

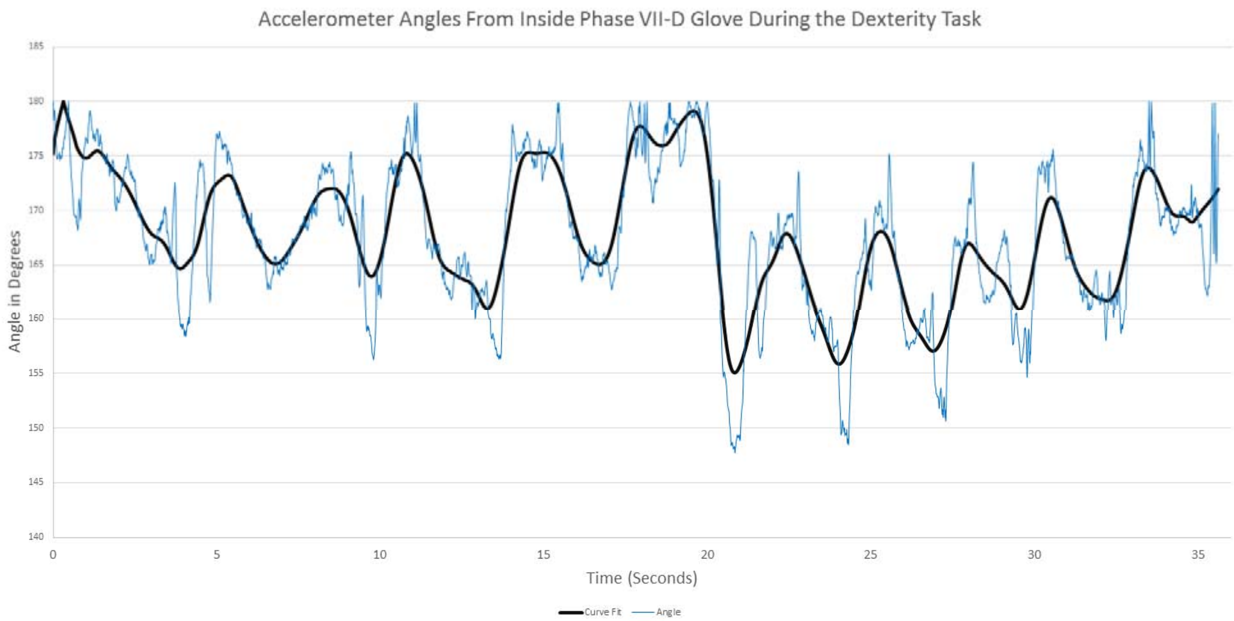

Figure 9. Wrist angles reached during the dexterity task. Data taken using accelerometers placed across the wrist to monitor flexion and extension from a single test subject. 10 repetitive movement are highlighted by the curve fit line, shown in black.

	Inside		TMG Layer	
	Flexion	Extension	Flexion	Extension
Series 4000	136.58±9.6	152.2±24.8	127.67±14.6	160.3±35.5
Phase VI	130.48±8.9	152.96±30.8	128.4±36.3	152.97±53.3
Phase VII-D*	138.14±5.4	171.12±8.1	138.46±5.4	172.37±6.6

Table 4. Maximum flexion and enxtension angles reached during dexterity task. *Only two subjects were tested with the Phase VII-D

IV. Conclusion

This feasibility study has provided an initial insight into the applicability of these sensors for monitoring and measuring joint movement in the hand while performed gloved operations. The accelerometers were able to detect movements in the wrist and reported joint angles that are to be expected at a maximum flexion or extension. The bend sensors placed on the PIP and DIP joints also performed well, however only under circumstances where the joint was flexed to its maximum and even then they simply reported that the extreme was reached. Ultimately it was not possible to approximate the actual joint angle to anywhere near its true state using the bend sensors chosen for this study but they were able to track a general angle range needed for completing a task. Tracking of repetitive movement through a motion with reasonable accuracy for the finger and wrist joints was also possible.

Working with an augemented comfort glove on the hand all test subjects described their experience wearing the sensor glove positively. All reported a nominal fit (very minor looseness or tightness) and remarked that there was nothing impeding their ability to normally move and manipulate their fingers, pinch grip objects, or feel with their hands and fingertips. The sensors themselves were not noticed by the subjects and they were comfortable working in the instrumented glove.

Future work will hopefully refine testing with the accelerometers and add additional hardware to track lateral joint movements such as wrist adduction and abduction.

Appendix

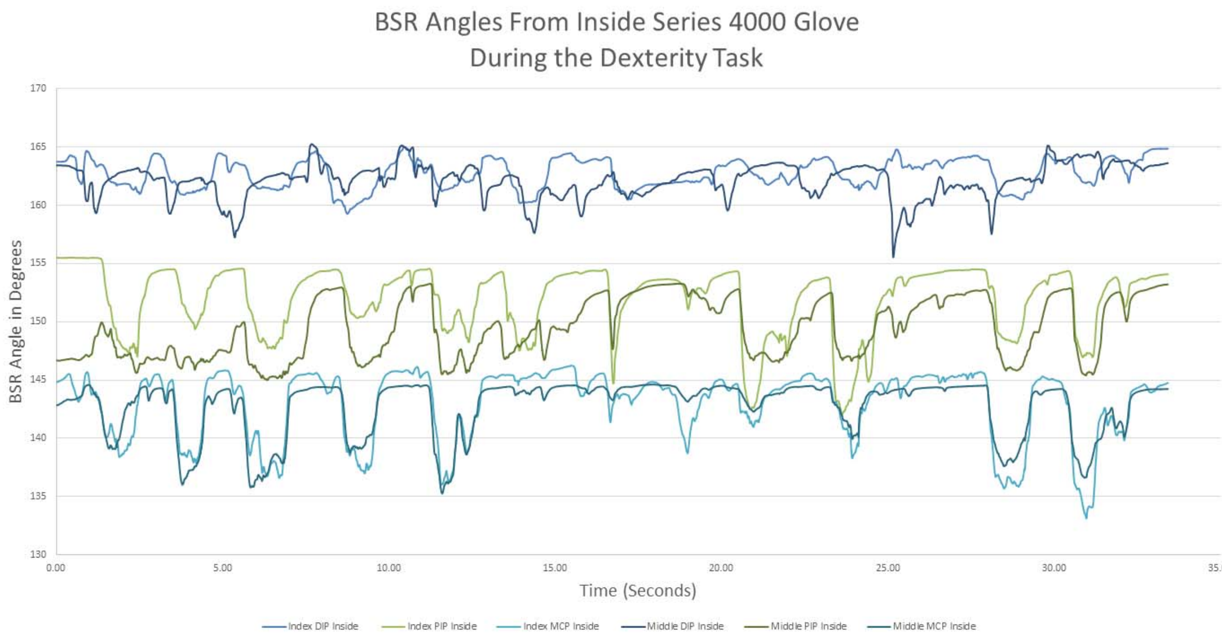

Figure 10. BSR data collected from a single subject during the dexterity task for the middle and index finger joints. Complementary joints are clearly shown to move in a similar range to complete the task.

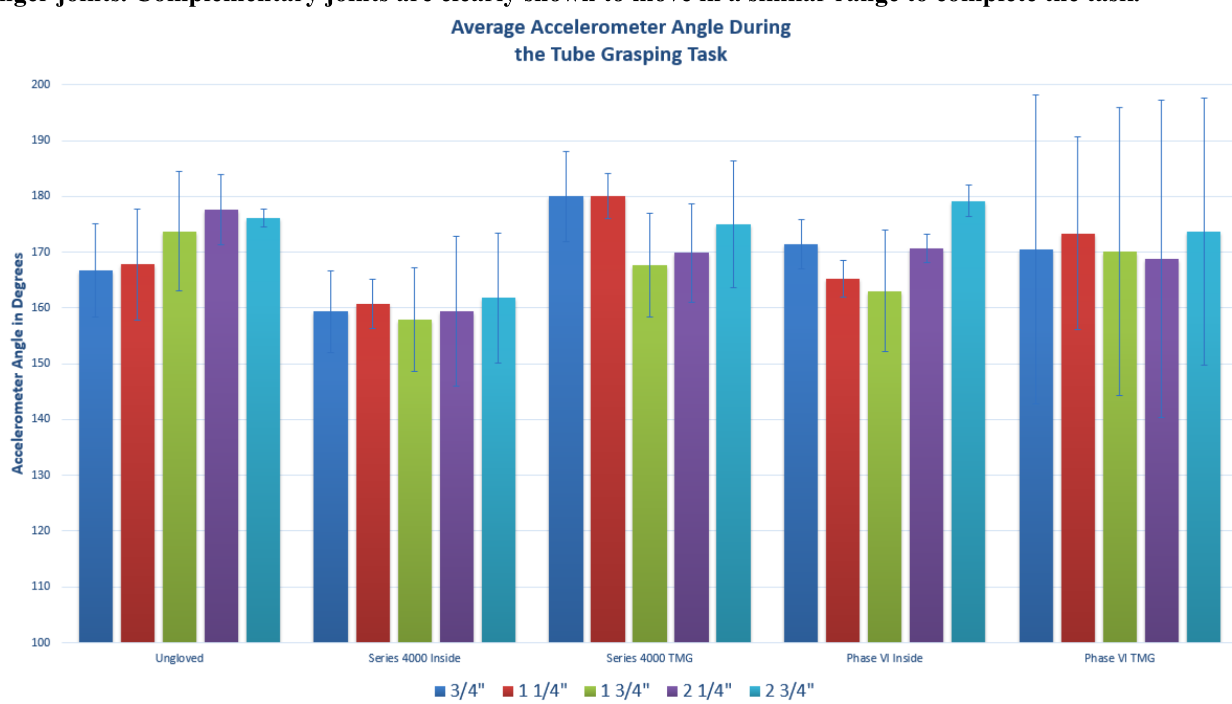

Figure 11. Average accelerometer angle reached during the tube grasping task from inside the glove.

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